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# Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change

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## ABSTRACT

Flood risk will increase in many areas around the world due to climate change and increase in economic exposure. This implies that adequate flood insurance schemes are needed to adapt to increasing flood risk and to minimise welfare losses for households in flood-prone areas. Flood insurance markets may need reform to offer sufficient and affordable financial protection and incentives for risk reduction. Here, we present the results of a study that aims to evaluate the ability of flood insurance arrangements in Europe to cope with trends in flood risk, using criteria that encompass common elements of the policy debate on flood insurance reform. We show that the average risk-based flood insurance premium could double between 2015 and 2055 in the absence of more risk reduction by households exposed to flooding. We show that part of the expected future increase in flood risk could be limited by flood insurance mechanisms that better incentivise risk reduction by policyholders, which lowers vulnerability. The affordability of flood insurance can be improved by introducing the key features of public-private partnerships (PPPs), which include public reinsurance, limited premium cross-subsidisation between low- and high-risk households, and incentives for policyholder-level risk reduction. These findings were evaluated in a comprehensive sensitivity analysis and support ongoing reforms in Europe and abroad that move towards risk-based premiums and link insurance with risk reduction, strengthen purchase requirements, and engage in multi-stakeholder partnerships.

## 1. Introduction

Flooding has been considered the natural hazard with the largest impact on society (CRED-UNISDR, 2015). Moreover, future flood risk will increase due to changes in flood hazards (flood frequency and intensity), exposure (values at risk), and vulnerability (the susceptibility to losses). The increase in flood risk due to socioeconomic development and climate change (IPCC, 2018) has placed growing pressure on insurance markets (Mechler et al., 2014; European Commission, 2017a,b; Cremades et al., 2018). This has resulted in declining welfare for those in flood-prone areas, for example, due to rising insurance premiums or uncertainty over future insurance coverage as risks become perceived as less insurable. Moreover, the increasing flood risk has initiated discussions about insurance market reforms (Michel-Kerjan and Kunreuther, 2011; European Commission, 2013; Surminski et al., 2015). For instance, in the United States, it is being debated whether flood risk can be privately insured (Michel-Kerjan et al., 2015; Kousky et al.,

2018) and which insurance mechanisms can provide better incentives for policyholder risk reduction (Kunreuther, 2015b; Kousky et al., 2018). Such incentives are important because policyholders can lower potential flood impacts (Hudson et al., 2016; Surminski et al., 2016; Aerts et al., 2018), for instance, by floodproofing buildings. Floodproofing consists of property-level measures which, for example, limit the potential damage once water has entered a building (known as wet floodproofing) or attempt to prevent water from entering a building (known as dry floodproofing).

Flood insurance reform is also being debated in Europe, where each country has developed particular insurance arrangements as a result of different risk profiles and public policy preferences (Surminski, 2017). One feature of the discussion about flood insurance reforms is the desirability of replacing fixed-rate insurance premiums with risk-based premiums (European Commission, 2013). Risk-based premiums may, in theory, incentivise damage mitigation by rewarding those who reduce risk with premium discounts (Lamond and Penning-Rowsell, 2014). The

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aggregated effects of individual action could provide a noticeable contribution to overall risk reduction, in turn lowering pressure on insurance markets. However, a disadvantage of risk-based premiums is that they may be unaffordable for low-income households in high-risk areas (DEFRA, 2011; Hudson et al., 2016; FEMA, 2018; Hudson, 2018). Debates about flood insurance reforms have also focussed on the desirability of different degrees of government and private sector involvement and whether coverage should be mandated or voluntary.

The main objective of this paper is to conduct a comparative analysis of a range of flood insurance market structures across Europe in relation to changing flood risk to identify common patterns of desirable characteristics of different types of flood insurance arrangements. This can provide a starting point for future flood insurance market reforms across Europe. For this investigation, we couple pre-existing models of insurance sectors, consumer behaviour, and flood risk in a single model evaluation framework, called the Dynamic Integrated Flood and Insurance (DIFI) model, so that a holistic assessment can take place. Such an analysis should account for the risk management objectives of countries because the development of disaster insurance occurs in response to public policy choices based on these objectives (Surminski, 2017). The DIFI model evaluation is conducted from the perspective of policymakers who wish to promote disaster insurance markets that manage the trade-offs between important insurance market outcomes. To account for these trade-offs, we conduct a multi-criteria analysis (MCA) of the key evaluation criteria, where the weights associated with each criterion act as a proxy for the risk management objective. Our research directions are extensions of the previous literature, which has focussed on qualitative evaluations of flood insurance markets (Michel-Kerjan and Kunreuther, 2011) or evaluations of a single market structure (Hudson et al., 2016). Due to limited information on household-level risk perception and mitigation efforts at the European scale, we employ a stylised scenario approach in a unified modelling framework, for which we perform an extensive sensitivity analysis. Moreover, an established modular model framework can act as a basis for future research as the DIFI model can be updated when new information becomes available, such as on flood risk or property-level behaviour. Our evaluation of stylised flood insurance arrangements allows for drawing generalisable lessons which are also applicable outside of Europe.

## 2. Methods

An evaluation of flood insurance market structures suitable for policymakers requires an analysis of economic efficiency and equity of different market features. We define efficiency as incentives for risk reduction that originate from the ability of insurance to send a price signal of risk (Baur, 2016). Moreover, low premium costs for households can lead to higher coverage levels, as noted in Lamond and Penning-Rowsell (2014). Whilst there is no universal definition of equity (Thaler and Hartmann, 2016), we focus on its distributive aspects by recognising that those threatened by flooding should have equal opportunities to purchase flood insurance and that risk-spreading mechanisms, like insurance, include principles of solidarity (Johnson et al., 2007; Thaler and Hartmann, 2016; Sayers et al., 2018; Thaler et al., 2018). Therefore, equity is taken to mean the affordability of premiums and the degree of risk sharing amongst households facing high and low flood risk.

We employ the DIFI model to assess the criteria listed in Table 1 for two time periods (2015–2035 and 2035–2055) to conduct a holistic evaluation of the range of different flood insurance market structures for a country. We design six categories of stylised market structures, which capture the core market features that influence the evaluation criteria, to evaluate existing structures in European countries and the benefits of market reform—for example, the drivers of insurance purchase (e.g., voluntary or mandated) or the differentiation of insurance premiums according to risk.

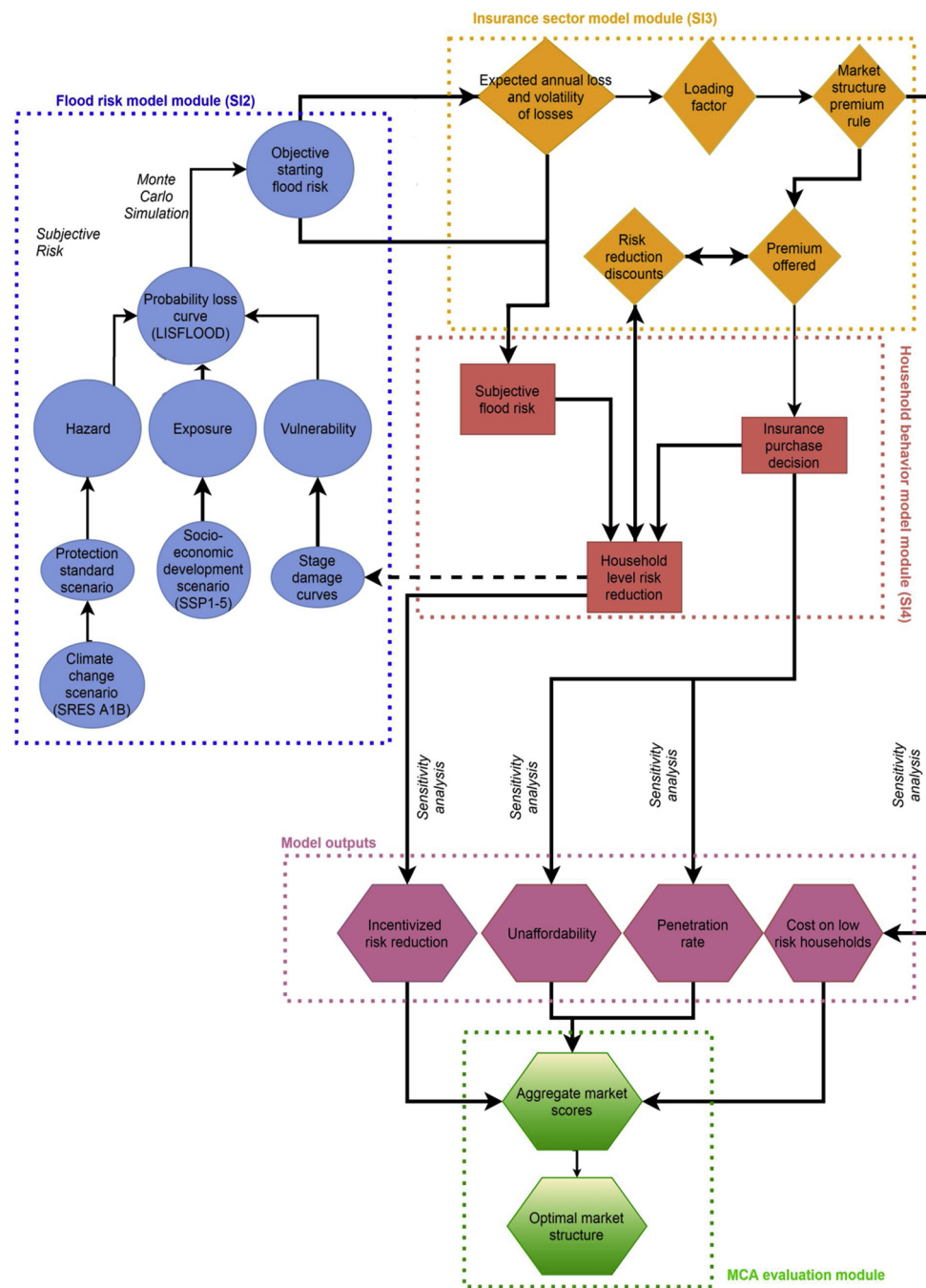
Our evaluation criteria are based on the debate surrounding flood insurance mechanisms as collected through a literature review (see SI8.1). This assessment highlights the importance of the following desirable characteristics of flood insurance arrangements: 1) the overall insurance penetration rate, 2) incentivised risk mitigation, 3) the ability to absorb large losses, 4) the ability to provide quick and certain compensation, and 5) the affordability and availability of insurance. These characteristics are further operationalised in our study according to the criteria in Table 1, which have been derived as follows. Criteria 1 and 2 are the aforementioned benefits of higher penetration rates and risk mitigation efforts by households. The Solvency II European Union legislation requires the compliance of European insurers to an annual insolvency probability of 0.5%. Therefore, insurers are already regulated to be able to absorb a large loss, which implies that characteristic 3 is met and does not need to be included as a separate criterion in our study. Similarly, characteristic 4 is met as this study focusses on formal flood insurance arrangements which provide quick and certain compensation. Characteristic 5 is further refined into costs imposed on low-risk households (criteria 3) and unaffordability of insurance for high-risk households (criteria 4) to capture the core equity concerns.

These criteria were drawn from literature regarding flood, and natural hazard, insurance (see SI8.1.1). This was complemented by a qualitative assessment of responses collected from a stakeholder engagement process (see SI8.1.2). The purpose of the stakeholder engagement process was to get a qualitative check of the MCA criteria and weighting derived from the literature review. However, whilst the stakeholder engagement confirmed that the selected criteria were suitable, the sample was not fully representative of all stakeholders or Europe as a whole. Nevertheless, since our MCA approach is based on the literature review, it does not strongly rely on the implications arising from the stakeholder consultation.

Our final four criteria in Table 1 closely match the criteria used by Hochrainer-Stigler and Lorant (2018) for an MCA of disaster risk management partnerships across Europe. Their selected criteria are economic efficiency (costs of insurance), risk reduction incentives, equity (solidarity and decreasing inequalities), and feasibility. Whilst Hochrainer-Stigler and Lorant (2018) derived these criteria from a different process, they strongly resemble our selections, which affords confidence in their suitability. Within our MCA framework, each of the four evaluation criteria in Table 1 are associated with a specific weight. Altering the size of the weights changes the relative importance of the evaluation criteria. As such, different weighting schemes represent different public policy objectives from national solidarity (a focus on affordability and market penetration rates) to insurance being a private matter (a focus on risk signalling). The relative importance attached to each of these criteria can change the outcomes of the analysis regarding the optimal market structure.

**Table 1**  
Summary and definition of the evaluation criteria estimated by the DIFI model.

	Definition	Benefit/Cost
<b>Criterion 1: Insurance penetration rate</b>	The average percentage of households with high flood risk that buy sufficient insurance at the national level	Benefit
<b>Criterion 2: Incentivised risk reduction</b>	The total net present value (NPV) of incentivised risk reduction conducted by households at the national level	Benefit
<b>Criterion 3: Cost on low-risk households</b>	The NPV of the subsidy of high-risk households paid by low-risk households, aggregated to the national level	Cost
<b>Criterion 4: Unaffordability of insurance</b>	The NPV of the magnitude of unaffordability, measured as the portion of premiums that cannot be paid from a poverty-adjusted disposable income at the national level	Cost



**Fig. 1.** Flow chart of the DIFI model version 1.0 modelling scheme.

Note: Blue circles represent the flood risk model components, red diamonds represent insurer behaviour, red rectangles represent policyholder behaviour, and green hexagons represent the multi-criteria analysis. The combined flood risk model, insurer, and policyholder behaviour elements form the DIFI model.

The DIFI modelling framework is presented in Fig. 1 and explained in detail in the supplementary information (SI) section SI1. The model consists of several modules: flood risk assessment under climate and socioeconomic change (SI2), insurance sector (SI3), and consumer behaviour (SI4). Based on the flood risk assessment, the DIFI model calculates flood insurance premiums (SI3) using the premium setting rules developed in Paudel et al. (2015) and Paudel et al. (2013) and simulates consumer behaviour dependent on the flood insurance market structure (see SI4). Consumer decisions involve purchasing insurance and investing in flood damage mitigation measures, which is determined in a cost-benefit assessment that applies a subjective expected utility framework. Depending on the insurance market structure, incentives for risk mitigation resulting from premium discounts are included. The

model was used to estimate the evaluation criteria in Table 1, which serve as input for the final evaluation framework (SI5). This evaluation is based on a comparative analysis to provide an indication of the relative benefits of the different insurance market structures, which are robust to some of the uncertainty in the model regarding the precise estimated criteria values. The criteria were estimated over two twenty-year periods: 2015–2035 and 2035–2055. The focus of the model is on those households at highest risk (i.e., those living in the area that can be affected by the one in one-hundred-year flood).

## 2.1. Flood risk modelling (SI2)

An existing coupled hydrological-flood-damage model (LISFLOOD)

at the European scale estimates the current and future risk of riverine floods across Europe, as presented in Feyen et al. (2012) and Rojas et al. (2013).

The combined model estimates the household-level loss  $[L(p)_{j,t}]$  from a flood with an exceedance probability (occurrence probability) of  $p$  in NUTS 2 region  $j$  at time  $t$  given a certain level of flood protection ( $PS_j$ ).  $L(p)_{j,t}$  is an increasing function of hazard  $[H(p)_{j,t}]$ , exposure ( $E_{j,t}$ ), and vulnerability ( $V_{j,t}$ ), which is shared over households at risk ( $N_{j,t}$ ), as shown in Eq. (1). Eq. (1) estimates the average flood damage per household from a given flood event. Kron (2005) provides definitions for exposure, vulnerability, and hazard: exposure is the value of assets that can be flooded, vulnerability is the degree to which assets are susceptible to being damaged, and hazard is defined as the magnitude of a hydrological event. The underlying flood risk model combines each of the above components using spatially referenced data to value the damage caused by a flood of a given exceedance probability. A damage probability curve is fitted based on a power-law function from several occurrence probabilities. Damage amounts for the following return periods are estimated as: 1/2, 1/5, 1/10, 1/20, 1/50, 1/100, 1/250, and 1/500. A Monte Carlo simulation using these return periods produces an estimate of the annual expected flood loss per household and the variance of losses.

In estimating the annual expected flood loss per household, the presence of protection standards (i.e., dikes) is accounted for in the hazard element of the flood risk model. A country that lacks protection standards would calculate risk over the probability range  $[0, 1]$ . Following Jongman et al. (2014), the presence of protection standards truncates the upper bound from 1 to the flood probability that exceeds the protection standard ( $PS_j$ ). For example, a protection standard of 1% means that only a flood event with an exceedance probability equal to or smaller than 1% will cause an impact. It is assumed that protection standards are fixed over time (Winsemius et al., 2016; Alfieri et al., 2018; Voudoukas et al., 2018). This implies that government investments in flood protection infrastructure maintain a constant dike failure probability when river discharges alter as a result of climate change. The values of  $PS_j$  used are taken from Jongman et al. (2014), who provide an estimate of regional protection standards in Europe.

$$L(p)_{j,t} = \frac{f(H(p)_{j,t}, E_{j,t}, V_{j,t})}{N_{j,t}} |PS_j \quad (1)$$

The output of the coupled hydrological-flood-damage model is converted into average annual expected losses for households in an area with a flood probability of at least 1% in the absence of protection standards. This area is defined as having high flood risk, which is consistent with Schwarze and Wagner (2007) and FEMA (2016). Low-risk households are those with a flood occurrence probability below 1% (in the absence of protection standards). Future flood risk is modelled by assuming that climate changes follow the SRES A1 scenario. Moreover, future exposed assets and population are estimated by rescaling flood impacts through the ratio of the future and baseline real GDP or population according to the ensemble mean of the various shared socioeconomic pathway (SSP) scenarios (Rojas et al., 2013). Therefore, all estimated insurance premiums are in real terms.

The underlying hydrological-flood-damage model estimates the current and future risk of riverine floods across Europe at a 100 m  $\times$  100 m (gridded) scale (Feyen et al., 2012; Rojas et al., 2013). However, the use of very detailed data used in practise entail high transaction costs for insurance companies as such information is not freely accessible (Osberghaus, 2015), which means that calculating premiums on this level may be infeasible (Porrini and Schwarze, 2014). Therefore, the estimated risk is aggregated to the NUTS 2 level, which is considered a suitable regional classification. Second, the obligation to buy insurance, along with the geographical size of the pool in which many risks are spread, eliminates concerns about adverse selection that may arise when premiums are set on an individual basis

(see Section 2.2).

Details of the flood risk modelling approach are provided in SI2.

## 2.2. Insurance sector (SI3)

We assume that each country under investigation has an insurance market that is willing to provide, and capable of providing, flood insurance to consumers as long as the consumer pays the offered premium. Moreover, we assume that the insurance policies offered provide sufficient coverage to avoid underinsurance. Due to this assumption, the DIFI model only captures underinsurance through lower penetration rates.

The insurance sector module uses the objective risk outcomes of the flood risk model to set insurance premiums (SI3.1), given the premium loading factors that depend on the market structure in which they operate (SI3.2). The primary insurance market (i.e., bought by households) is assumed to be highly competitive, whilst the reinsurance market (i.e., insurance bought by insurers) is assumed to be less so. Insurers will offer insurance premium discounts if a household employs risk mitigation measures. In all modelled insurance market structures, the insurance premium is calculated at the start of the year and is set at that value until the next year before considering household-level mitigation efforts. Only households that employ mitigation measures can receive premium discounts in line with the reduced risk (SI3.3).

We developed six flood insurance market structures (M1–M6), Table 2, based on information collected about European market structures (SI8) that reflect a range of market features. These are stylised market structures and, as such, capture the average performances and characteristics of a market structure. We focus on the market features that are important for generating the evaluation criteria. Therefore, there may be deviation between the stylised assumptions and what occurs in practise. However, a large-scale application, such as the DIFI model, inevitably requires that some details of current existing insurance market structures cannot be represented in the model. Nevertheless, this approach is in line with our aim to arrive at insights into general patterns across the European Union about the performance of flood insurance market structures in light of climate change and desirable reforms. Moreover, focussing the analysis on country-specific examples would not enable the study of potential counterfactual markets (e.g., France moving from a public solidarity-based market to a more private-sector-orientated market), whilst this is feasible with our stylised market structures.

The main structure of insurance premiums (across market structures) is based on Hudson et al. (2016); Paudel et al. (2013), and Paudel et al. (2015). Here, the premium which insurers charge households differs across market structures and takes the form displayed in Eq. (2), where:  $\pi_{i,j,t,s}$  represents the premium charged to household  $i$  in NUTS 2 region  $j$  at time  $t$  under market structure  $s$ , with  $s$  taking the value 1 for the solidarity market structure, 2 for the PPP market, 3 for the voluntary market structure, 4 for the semi-voluntary structure, and 5 and 6 are the semi, voluntary, and full PPP markets, respectively;  $ER_{DRR}$  is the discount that insurers will provide depending on the level of household risk reduction, which entails either one or both of dry and wet flood-proofing, as described in section SI3.2; and  $\bar{\pi}_{j,t,s}$  is the baseline average risk per household within a particular market structure for a given NUTS 2 region.

$$\pi_{i,j,t,s} = (1 - ER_{DRR}) \bar{\pi}_{j,t,s} \quad (2)$$

The precise value of  $\bar{\pi}_{j,t,s}$  differs across market structures, as shown in SI3. However, the key difference between market structures is how strongly  $\bar{\pi}_{j,t,s}$  is connected to the risk that a household may face. A market with no connection to risk will have the lowest premiums for high-risk households, whilst one with a strong connection to risk is likely to have the highest premiums for these households. However, these premiums may be limited if households do implement risk-reducing measures.



**Table 2**  
A summary of flood insurance structures.

Structure group	Sector covering flood risk	Key market features	Potential insurance penetration rate (% with an insurance policy)	Risk sharing across high- and low-risk policyholders	Countries allocated
<b>M1. Solidarity public structure</b>	Public	Mandated purchase requirement Premiums unconnected to risk Government support for insurers	Very high penetration rate (95–100%) due to direct purchase requirement	A high degree of risk sharing due to mandated purchase and non-risk-based premiums distributing risk widely	France, Belgium, Spain, Romania
<b>M2. Semi-voluntary private market</b>	Private	No public flood damage compensation Purchase is connected to mortgage or rental conditions Premiums are risk based No government support for insurers	High penetration rate (75–100%) due to indirect purchase requirements. Damage to buildings is more often insured than contents due to mortgage requirements.	A moderate degree of risk sharing due to indirectly mandated purchase and risk-based premiums	Sweden, Ireland, Hungary, Finland
<b>M3. Voluntary private market</b>	Private	No public flood damage compensation No government-, product-, or dwelling-related mandated purchase requirement Premiums are risk based	Medium to low penetration rates (0–60%) if government support is uncertain. Very low penetration rates (0–25%) if government support is certain.	A low degree of risk sharing due to voluntary purchase and risk-based premiums	Austria, Netherlands, Germany, Italy, Portugal, Luxembourg, Greece, Poland, Czech Republic, Slovakia, Slovenia, Croatia, Bulgaria, Latvia, Estonia, Lithuania
<b>M4. Semi-voluntary PPP market</b>	Public-Private	Possible public flood damage compensation Same overall features as M2 except for the introduction of a government reinsurer for extreme risk. Private reinsurance remains available for less extreme events. Additionally, now there is no public flood damage compensation.	High penetration rate (75–100%) due to indirect purchase requirements	A moderate degree of risk sharing due to indirectly mandated purchase and risk-based premiums	Hypothetical market structure
<b>M5. Voluntary PPP market</b>	Public-Private	Same overall features as M3 except for the introduction of a government reinsurer for extreme risk. Private reinsurance remains available for less extreme events. Additionally, now there is no public flood damage compensation.	Medium to low penetration rate since premiums are lower than M3, so demand should be higher, given the presence of any public compensation in M3.	A low degree of risk sharing due to voluntary purchase and risk-based premiums	Hypothetical market structure
<b>M6. Public-private partnership (PPP) market</b>	Public-Private	Purchase is connected to mortgage lender or rental conditions. Premiums are partially risk based. Governmental frameworks to support insurers. No public flood damage compensation	High penetration rate (75–100%); higher than M2 due to the cap on the maximum premium size but lower than M1 due to a stronger connection with risk	Moderate to high degree of risk sharing but less than M1 due to indirectly mandated purchase and semi-risk-based premiums	UK

Note: Romania displays many of the criteria of M1 with the exception of the insurance penetration rate being less than 20% due to poor enforcement of the purchase requirements. Therefore, it has been placed within M1 as a stylised market structure. See S18.2 for details.

The proposed market structures are:

**M1—solidarity public structure:** All households must buy an insurance policy at a fixed price, regardless of their objective flood risk and personal preferences (e.g., an automatic extension of insurance policies). The premium is determined by equally sharing risks across all households (in a nation) regardless of their individual risk (SI3.1.1).

**M2—The semi-voluntary private market** is similar to the voluntary private market (SI3.1.3) except that mortgage, or rental, conditions have a requirement or tradition of comprehensive insurance coverage. However, coverage is not complete because those without mortgages are not compelled to insure. Although mortgaged buildings are almost universally insured, contents within a building are less often insured (Surminski and Eldridge, 2015), especially for low-income households (O'Neill and O'Neill, 2012; FEMA, 2018).

**M3—voluntary private market:** Households have the free choice of whether to buy flood insurance at risk-based premiums. Policyholders pay a premium in proportion to their annual expected loss, plus a surcharge covering insurer cost, profit, and risk aversion (SI3.1.3).

**M4—Semi-voluntary PPP** is similar to the semi-voluntary private market except that it is supported by a PPP. This is assumed to be a not-for-profit public reinsurer who charges a reinsurance premium for coverage. Introducing a public non-profit and risk-neutral reinsurer for a portion of risk will limit insurance premiums for households.

**M5—Voluntary PPP** has no purchase requirements and is similar to the voluntary private market except that it is supported by a not-for-profit public reinsurer.

**M6—The PPP market** is a compromise between M1 and M5. It connects insurance coverage with mortgage (or rental) conditions, it contains a public reinsurer (SI3.1.2), and premiums are risk based up to a threshold level at which the premium is capped (with possible surcharges to cover administrative costs). To maintain solvency, this shortfall is accounted for by placing a surcharge on the lower-risk households. This outcome can also be achieved by raising levies, similar to Flood Re. This organisation uses levies to generate a sufficient capital reserve that can be used to provide indemnity payments when the accessible financial resources prove insufficient.

Both private and public reinsurers charge a premium to primary insurers for the coverage they provide. However, reinsurers apply a premium surcharge due to their risk aversion (Paudel et al., 2015), whilst, due to the greater risk-spreading potential (e.g., taxation), public reinsurers are risk neutral and do not require a surcharge. However, providing public sector reinsurance facilities could be problematic as levels of risk aversion will vary amongst governments and are dependent on financial circumstances. Refocusing the European Union Solidarity Fund can be an alternative if it is reformed to act as a reinsurer or a co-insurance-style pool across the European Union. This would provide a great deal of geographical diversification, and such a reorientation is in line with a proposal directed towards the European Union Solidarity Fund in Hochrainer et al. (2010).

In each of the market structures above, the first role of the government is investing in risk-reduction infrastructure to maintain protection standards (see Section 2.1). These flood protection standards keep flood probabilities constant under changing climate conditions, which is important for creating an environment for insurance markets to operate and maintain insurability of flood risk (Surminski and Thieken, 2017; Insurance Europe, 2018c; The Geneva Association, 2018).

The second role of the government occurs in M4 to M6, which are extensions of M1 to M3, in which the government acts as a reinsurer for the extreme element of flood risk that is expensive to reinsure privately (Paudel et al., 2015). Even though private-sector reinsurance is available, such coverage is more expensive compared to the publicly provided reinsurance. In all market structures, the government does not directly subsidise premiums.

A country is allocated to a stylised market based on how closely a market meets the following features: purchase requirements and the

connection between premiums and risk. These points of comparison are the main aspects of the market that generate the four aforementioned evaluation criteria. This is because purchase requirements drive insurance penetration rates (Golnaraghi et al., 2017; Schanz, 2018), which can be influenced by legal obligations or by product design (Insurance Europe, 2018a) and the demand for non-insurance products (e.g., mortgages for which coverage is required). The link between premiums and risk can create trade-offs between affordability and the ability to incentivise risk reduction (Hudson et al., 2016). Finally, the combination of these two features determines the cross subsidy required between high- and low-risk policyholders.

Once an initial allocation has been made, the choice is refined based on the degree of government support available for the insurance industry and for households affected by flooding. For instance, public reinsurance (as is possible under M1) helps to keep premiums low by replacing potentially high private (risk-averse) reinsurance premiums with a lower public (risk-neutral) reinsurance premium. Also, the presence of government compensation can create a charity hazard which lowers the demand for insurance as the cost of not being insured is lower (Raschky and Weck-Hannemann, 2007). Both of these features are important for determining voluntary demand. Higher premiums can reduce the demand for insurance as the perceived benefits of insurance are smaller or the premium becomes unaffordable.

An assumption following from our assessment of fluvial flood risk is that flood insurance is treated as a stand-alone insurance product. However, flood insurance is often bundled with other natural hazard risks in countries with high penetration rates. In practise, such bundling often implies having semi-voluntary purchase requirements since flood coverage is commonly bundled with other risks like fire, for which it is compulsory to have coverage to meet mortgage requirements (see European Commission, 2017a, for example). Therefore, in our solidarity, semi-voluntary, and PPP markets, the insurance product could be considered part of a wider bundle of natural hazard risks. Bundling reduces the need for a conscious decision to buy a specific type of insurance. This is accounted for in our consumer behaviour model since, in semi-voluntary markets, flood insurance demand is not modelled as a conscious choice in an expected utility maximisation decision rule but instead as a fixed percentage that is calibrated based on observed penetration rates in these markets. Bundling could reduce the transparency of the insurance premium because it is based on a combination of risks, which may lower incentives for the policyholder to take measures to limit flood risk. This could be limited by better documentation of the risk elements that make up the premium and by reinforcing the link with property-level risk management, for example, by offering discounts to policyholders who take measures that limit their risk.

### 2.3. Household behaviour (SI4)

Details of the household behaviour modelling approach are provided in SI4 and are summarised here. Household behaviour consists of two decisions: to buy insurance (SI4.1) and to employ risk-mitigation measures (SI4.2).

A household makes an initial decision to undertake a risk mitigation measure based on the household's subjective level of flood risk and, as such, the perceived benefits of mitigation, which can be over- or underestimated. Next, the household makes a decision to buy insurance (M2 and M4) or is compelled to do so (the remaining market structures). Unless households are mandated to buy insurance, they will only buy insurance if the subjective expected utility of being insured is larger than the expected utility of not being insured and if the premium is affordable (SI4.1). The subjective expected utility framework is a model of individual decision making under risk (Savage, 1954). Households' risk perceptions are expected to deviate from objective risk in terms of flood occurrence probabilities and the potential damage suffered.

The subjective risk perceptions are calibrated based on previous studies, as noted in SI4.1–SI4.2. However, there is limited information

available on the risk perceptions or mitigation behaviour of individuals across Europe. Therefore, we undertake a scenario approach in which we calibrate separate risk-perception distributions for simulating flood insurance demand and decisions to employ risk-reduction measures in the absence of insurance-based incentives. Perceptions of flood probability are based on empirical studies (Botzen et al., 2009, 2015), and perceptions of flood damage follow a generalised Pareto distribution, both of which are calibrated to match regional insurance demand in Germany (GDV, 2013). Germany was selected for this since it provides the most detailed information within Europe about voluntary flood insurance purchases. The demand for household-level risk-reduction measures is based on a subjective cost-benefit analysis in which the benefits relate to the perceived reduction of flood risk by implementing a risk-reduction measure. This variable accounts for the possible misperceptions of the flood probability, the expected flood loss, and the potential effectiveness of the risk-reduction measure, and its distribution has been calibrated to match the observed usage of dry and wet floodproofing measures as reported in the following three studies: Kreibich et al. (2005), Bubeck et al. (2012), and Poussin et al. (2013). In the absence of detailed data at the European level, we create three risk perception scenarios. We focus on the average outcomes across these three risk perception scenarios in a similar way to how many flood risk assessment studies use ensemble climate model outcomes. However, this has the implication that the precise values of household behaviour resulting from these scenarios should be treated with caution. Nevertheless, the relative outcomes across the various scenarios and market structures may be less sensitive to uncertainty in this aspect of the model because each market is exposed to the same distributions of subjective risk perceptions.

A household with insurance coverage will be exposed to a potential premium discount if the household employs mitigation measures. This may promote a household to employ a mitigation measure if it did not do so initially. The more strongly premiums are risk based, the stronger this incentive will be (e.g., in the solidarity public structure, incentives are negligible). It should be noted that in some market structures and areas, the flood insurance premium, and hence the premium discount for taking risk-mitigation measures, is too low to act as an incentive to change policyholder behaviour. This can occur in areas with a low flood risk where employing flood risk-mitigation measures is not cost-effective. Moreover, this can happen in countries with a high degree of cross-subsidisation of premiums, which occurs in the solidarity market structure (M1). Both of these aspects are captured by our model, and indeed we find that the incentivised risk reduction through insurance is low in these market structures and in areas facing lower risk.

Moreover, there is an indirect interaction between household-level risk-reduction measures and the flood protection standards maintained by the government because the latter influence flood insurance premiums and the expected value of avoided flood damage by floodproofing measures. For instance, flood risk is low in areas with high flood protection standards, which results in lower premiums and lower benefits for household risk reduction in terms of either avoided flood damage or premium discounts compared to areas with low flood protection standards.

The household behaviour modelling approach is based on Hudson et al. (2016) and now includes budget constraints (SI4). The budget constraint implies that a household will only buy insurance if it is affordable to do so based on its income at the time of the decision. Including the budget constraint captures the tendency of higher-income households to be insured more often (Raschky et al., 2013). Insurance is deemed unaffordable when the premium to be paid is larger than the household's disposable income above the poverty line (Hudson et al., 2016; Zhao et al., 2016; FEMA, 2018). The total magnitude of insurance unaffordability is estimated as the sum of the unaffordable portion of insurance premiums (SI4.1). A similar budget constraint also applies to the employment of risk-reduction measures, where the measure is only taken if it is affordable at the time of purchase given any expenditure on

insurance. The reason is that whilst a measure may be cost-effective in the long run, a household is unlikely to employ such a measure when it is currently unaffordable (SI4.2). This way, our model accounts for different capabilities between high- and low-income households to take flood risk adaptation measures. An implication is that insurance is only able to incentivise risk reduction if both the premium and the measure are affordable.

#### 2.4. Overall market evaluation (SI5)

The MCA evaluation framework is based on the key evaluation criteria for the periods 2015–2035 and 2035–2055, as described in SI5. In an MCA framework, each of the key evaluation criteria can be associated with different weights as a measurement of the relative importance (trade-offs) that policymakers attach to one criterion as compared to the others.

The MCA method allows for identifying the relative benefits of the market structures and for finding the optimal market structures through a holistic comparative study of the evaluation criteria. The ensemble mean (across behaviour scenarios) of four criteria is aggregated from the NUTS 2 to the national level and standardised into a score for the structure within a country. This is done by creating a weighted sum across the four criteria for each market structure within a country.

In the MCA, the evaluation criteria are standardised and aggregated following Eq. (3).  $S^1_{c,s}$  is the score for market structure  $s$  in country  $c$  for the first period (or the second if  $S^2_{c,s}$ ). The values for each indicator ( $A^1_{c,s}$ ) are standardised since this allows the variables to have a common metric and to be weighted according to perceived importance. The standardisation process bounds score values by 0 and 1.

$$S^1_{c,s} = \frac{\sum_{n=1}^{n=11} \sum_{m=1}^{m=4} \omega_m^1 MCA_{j,t,s}}{11}, \text{ where } MCA_{m,j,t,s} = \begin{cases} \frac{A^1_{c,s} - A^{1,Min}_{c,s}}{A^{1,Max}_{c,s} - A^{1,Min}_{c,s}} & \text{if a benefit} \\ 1 - \frac{A^1_{m,j,t,s} - A^{1,Min}_{m,j,t,s}}{A^{1,Max}_{c,s} - A^{1,Min}_{c,s}} & \text{if a cost} \end{cases} \quad (3)$$

The possible choices for  $\{\omega_m^1\}$  can alter the overall attractiveness of the various market structures for each country. To account for the uncertainty in setting the weights, we use a range of weights to compare patterns of desirable market structures across different risk-management objectives. In particular, the following multiple sets of weights are used: (a) equal weights, where  $\omega = 1/4$ ; (b) one element is weighted at  $\omega = 2/5$  and the remaining two elements at  $\omega = 1/5$  (with an alternating element with the double weight); and (c) two elements are weighted at  $\omega = 3/10$  and the remaining elements at  $\omega = 1/5$  (with alternating elements with the higher weight). There are eleven unique combinations of weights which reflect systematic differences in the importance of outcomes. These weights have been set by the authors to model outcomes under a range of potential public policy objectives described in SI8. The evaluation criteria and weights are applied equally to all the countries studied. Our approach is similar to the MCA employed in Unterberger et al. (2019) to model objectives for public-sector flood risk management in Austria. Our MCA identifies the market structure that, on average, scored the highest across the eleven sets of risk-management objectives (as proxy measured by the different weighting schemes) to indicate the optimal market. This approach assumes that one set of risk-management objectives is not treated as more important than another, the implications of which are discussed in section

#### 2.5. Sensitivity analysis (SI6)

An extensive sensitivity analysis was conducted, the results of which are presented in SI6, to find if the results are overall robust to changes in model structure or parameter values. In particular, the assumptions tested in the sensitivity analysis were: uncertainty in risk and insurance



premium estimates (SI6.1), different flood risk scenarios (SI6.2), alternate construction of the insurance premium discount (SI6.3), using a single national pool of high-risk households rather than regional differentiation (SI6.4), alternative assumptions about the costs and effectiveness of risk-reduction measures (SI6.5), alternative assumptions on the utility function determining flood insurance demand (SI6.6), and a different MCA ranking scheme (SI6.7).

### 3. Results

#### 3.1. Flood insurance reform pathways

To our knowledge, this is the first large-scale study that integrates flood risk assessment, the insurance sector, and consumer behaviour in one modelling approach to assess insurance market structures against increasing flood risk. The DIFI model estimates that, on average, risk-based insurance premiums could double for the countries investigated between 2015 and 2055 if no flood insurance market reforms are undertaken. Hence, increasing flood risk will place pressures on stakeholders, such as insurers, to meet international agreements on disaster risk reduction, such as the Hyogo (Wilby and Keenan, 2012) and Sendai frameworks (UNISDR, 2015) and the Paris Agreement (UNFCCC, 2018). Insurance could play an important role in providing both financial protection against flood losses and incentives for risk reduction. Flood insurance arrangements require reform to cope with increasing risk, and we demonstrate that household-level risk-reduction measures can be incentivised through a stronger link between risk reduction and the premiums charged. This finding highlights the importance of developing partnerships between the insurance sector and other flood risk management stakeholders to overcome the barriers to establishing an active link between premiums and risk reduction, for example, using certification schemes of floodproofing practises (Golnaraghi et al., 2017).

More precisely, the DIFI model output produces an average household insurance premium that is lowest in the solidarity public structure (€5–€125 per year in 2015) and highest in the private voluntary markets (€30–€2000 per year in 2015). These differences in premiums translate into different rates of unaffordability due to the differing degrees of cross-subsidisation between high- and low-risk households. For instance, the voluntary private insurance premiums are unaffordable for about 21% of the regional population in high-risk areas (on average), whilst this is only 16% in the PPP market (see SI7.1). However, the cost for low-risk households is lowest when premiums are based on risk with limited cross-subsidisation.

The risk mitigation incentives from insurance are not found to be effective in the solidarity public structure since the potential premium discount is too low (an average of €14 per year in 2055); see SI7.2. The voluntary market structures offer stronger incentives of, on average, €500 per year. However, fewer households are exposed to this incentive due to the lower market penetration rate of flood insurance. This is because the premium is unaffordable for many households, or it is perceived as being too high compared with the benefits of insuring. The PPP markets are found to be more successful in incentivising dry floodproofing than wet floodproofing measures due to their higher investment costs. Overall, insurance is more affordable in PPP markets, which also have a higher penetration rate that enables more risk reduction through the insurance incentives.

Fig. 2A and B show how market structures would evolve from the current situation (2015) towards optimal structures for the period 2035–2055. During the 2015 to 2035 period, most countries are advised to move towards the semi-voluntary market (PPP) which entails reforms introducing public reinsurance and strengthening (indirect) purchase requirements. For the 2035 to 2055 period, the majority of countries will benefit from continued reform towards a full PPP market structure. For about a third of the countries, we estimate a reform pathway where the market structure evolves over time (see SI7.1).

This highlights that there may not be a single optimal market structure but a changing bundle of desirable features. Several studies have also argued that there is no one-size-fits-all solution for insurance markets (Surminski et al., 2016; Hochrainer-Stigler and Lorient, 2018; Raadgever et al., 2018). An example is the public response to the EC green paper on disaster insurance, which showed that many of the respondents were against the harmonisation of insurance regulations across the European Union (Surminski et al., 2015). Our study's focus, however, is on deriving general characteristics to guide reforms, and there are still many options for fine-tuning the exact method of implementation in a way that is in line with different preferences of local stakeholders. Moreover, there is not a single optimal market structure across periods and countries. Instead, we find that a process of continued reform over time is advisable for most of Europe: from the current market structure to the semi-voluntary PPP market and then towards the features of the PPP market.

Regardless of the absence of a single optimal market structure, altering market structures as suggested can improve the welfare of those living in flood-prone areas. This is because of the greater certainty in receiving suitable compensation after a flood or a greater sense of security due to being better prepared before a flood (see SI7.3). For instance, increased insurance coverage improves the welfare of a risk-averse household by exchanging an uncertain, and potentially catastrophic, loss from a flood for a certain, smaller payment in the form of an insurance premium. A higher market penetration of flood insurance can, therefore, be seen as welfare enhancing because of improved financial coverage against flood damage.

Moreover, from the policymaker perspective, uninsured flood impacts are undesirable as they are a driver of long-run negative macroeconomic impacts (Von Peter et al., 2012). Underinsurance is also a well-known issue in natural hazard insurance markets (The Geneva Association, 2018). For example, Austria has a penetration rate of nearly 85%, but less than 10% of the value exposed to flooding is insured (Insurance Europe, 2018b). In practise, coverage levels can vary amongst countries, which implies that flood insurance reforms should not only focus on obtaining a high market penetration but should also consider achieving sufficient coverage per policy. A closer collaboration of stakeholders in a PPP market can help to develop long-run mechanisms for limiting risks, like incentivising policyholder risk reduction, and for increasing coverage to limit the issue of underinsurance (Schanz, 2018; The Geneva Association, 2018).

The following findings are important for improving welfare: limited premium cross-subsidisation between high- and low-risk households, involvement of the government (or a transnational body) as reinsurer, incentives for policyholders to implement floodproofing measures to homes, purchase requirements such as mandating flood coverage, or connecting flood insurance coverage to mortgages or other more commonly acquired insurance policies such as fire. Such purchase requirements create a pool in which risks are shared between high- and low-risk households, and they also prevent adverse selection. The PPP market imposes lower costs on low-risk households than would occur under a solidarity market structure due to less premium cross-subsidisation between high- and low-risk households (see SI7.2). The PPP market manages to provide an acceptable trade-off between the unaffordability of risk-based premiums and the ability of such premiums to incentivise policyholders to employ risk-mitigation measures.

#### 3.2. Optimal market structures

As noted, the semi-voluntary PPP (M4) and PPP (M6) markets most often score highest in the MCA. In particular, their stylised market features lead to higher average MCA scores, as compared to the voluntary or solidarity market structures. This means that these PPP markets have stylised features that best manage the trade-offs amongst the criteria for a given level of risk within a region.

Although premiums are more often unaffordable and the

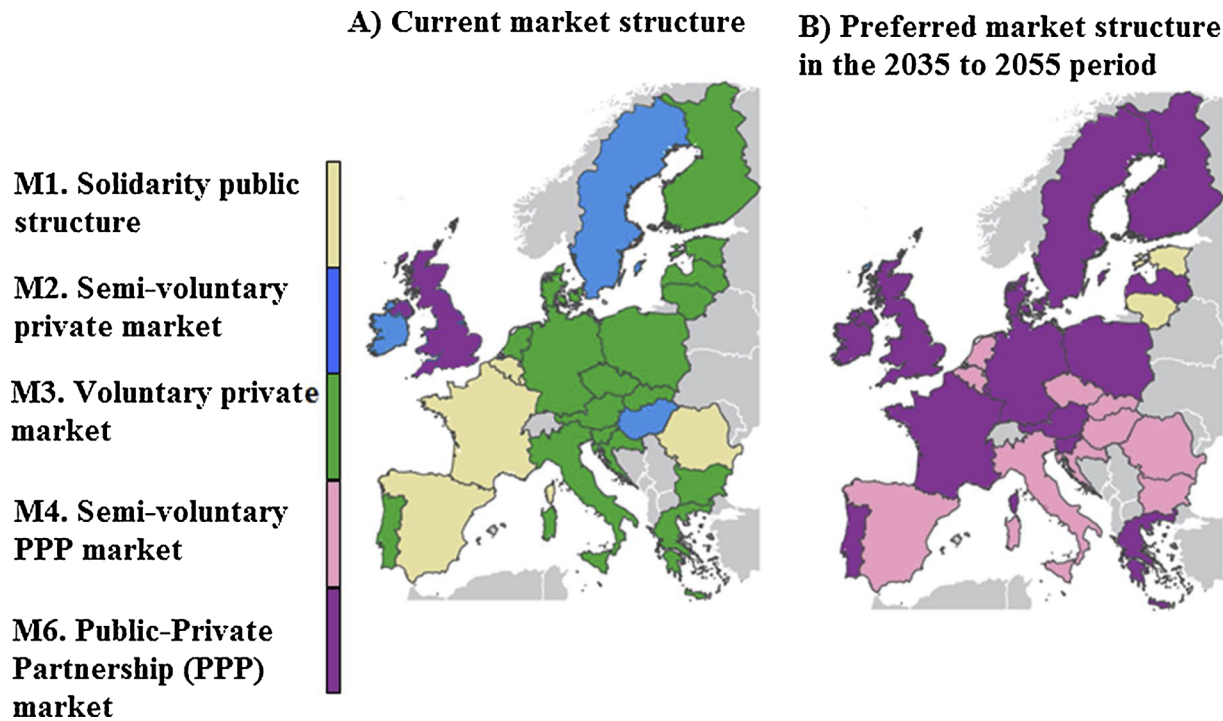


Fig. 2. Current flood insurance market structures (panel A) and market structure reforms suggested by the DIFI model for the period 2035–2055 (panel B).

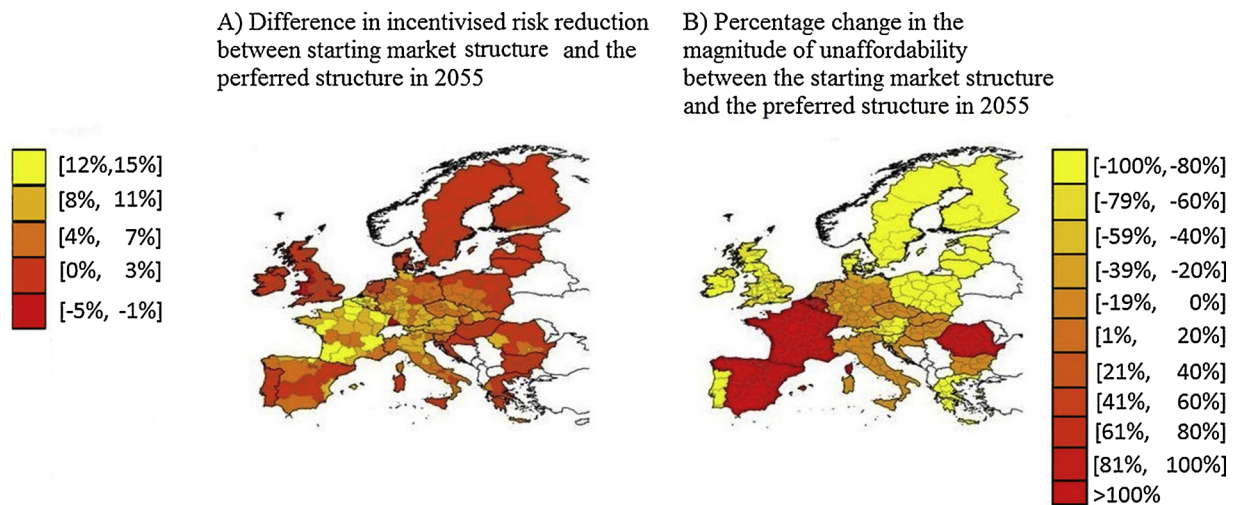


Fig. 3. Consequences of incentivised risk reduction (panel A) and unaffordability (panel B) of the insurance market reforms suggested by the DIFI model results for the year 2055, two elements of household welfare.

penetration rates are slightly lower in the semi-voluntary PPP and PPP markets, these two markets score systematically better than the solidarity public structure (M1) because they perform significantly better in incentivising risk reduction by policyholders. Moreover, this additional incentivised risk reduction lowers the premium burden on households in lower-risk areas. Even though the final MCA score is determined by each element, the main driver of the performance of the semi-voluntary PPP and PPP markets is the increase in risk reduction, which outweighs the negative impacts of lower penetration rates and higher unaffordability. The main advantage of the semi-voluntary PPP and PPP market structures compared with the semi-voluntary market structure (M2) is that the two PPP structures have lower premiums and, hence, fewer problems with unaffordability of premiums.

Moreover, these two markets also perform better than the voluntary private (M3) or PPP (M5) market structures due to the higher penetration rate as a result of the indirect and direct purchase requirements.

This has the effect that the risk-based premiums are able to incentivise additional risk reduction by many policyholders. The penetration rates under the voluntary markets are significantly lower, which implies few policyholders receive additional incentives to reduce risk through premium discounts. In the areas where the PPP market is preferred to the semi-voluntary PPP, the fully risk-based premiums in the latter market structure would increase premium unaffordability much more rapidly than they helped to promote additional risk reduction. The movement towards the PPP markets in this case indicates that slightly weakening the link between premiums and risk can reduce the burden of unaffordability whilst still promoting a sufficient degree of risk reduction. This combined effect results in an overall higher MCA score. The regions where the semi-voluntary PPP is preferred to the PPP have slightly lower risk overall, which means that a stronger link between risk and premiums is required to incentivise sufficient additional risk reduction.

### 3.3. Implication of proposed insurance reforms for risk mitigation and affordability of insurance

Fig. 3 shows that moving towards the optimal stylised structures with varying degrees of PPPs results in an improvement in the amount of risk mitigation undertaken by households across most areas (Fig. 3A) when premiums are (partly) risk based. The decision to floodproof properties under the existing market structures lowers residential risk on average by ~17% from 2015 to 2055. The optimal insurance market structure increases this value to between 20 and 26% due to stronger risk-mitigation incentives. Though these values are approximate, the key message is that strengthening insurance purchase requirements and policyholder risk mitigation can help to lower risk if the unaffordability concerns are alleviated.

However, for the currently employed solidarity market structures, the reform towards increased mitigation incentives comes at the expense of insurance affordability for high-risk households whilst reducing the costs placed on low-risk households (Fig. 3B). In contrast, for private insurance markets, the unaffordability of insurance outweighs the potential mitigation incentive of the insurance premiums. This implies that reform towards PPP is desirable. Unaffordability remains a concern even in the solidarity market structure, where the link between insurance and risk is weakest. This suggests that overcoming problems with unaffordability may require the use of public policies such as insurance vouchers for low-income households in high-risk areas (Kunreuther, 2008). An insurance voucher is provided by the government to low-income households for the proportion of the insurance premium deemed to be unaffordable. The vouchers are issued on a temporary basis to smooth the transition to new market structures. Whilst vouchers can ease the cost that high premiums place on low-income households, the vouchers should remain temporary to prevent an implicit subsidy for development in flood-prone areas (Kousky and Kunreuther, 2014).

Another way to improve affordability is to increase the sharing of losses over many policyholders through the introduction of purchase requirements. This policy reform expands the risk pool of insured households, which lowers premiums. Moreover, purchase requirements limit the threat of asymmetric information to cause market failures through adverse selection.

However, the introduction of purchase requirements, like in the PPP market, may also be politically difficult because it can be seen to limit consumer freedom. This issue is substantiated by discussions regarding insurance reforms in the Netherlands (Botzen, 2013) and Germany (Schwarze and Wagner, 2007). Additionally, conflicts with state aid regulations can arise. This can be seen from the United Kingdom's introduction of Flood Re, which would be partially funded by an industrywide levy. This planned reform received criticism as it would confer an economic advantage to the risk pool over its competitors, which conflicts with the European Union's state aid regulations (European Commission, 2015). Nevertheless, this was decided not to be the case, although it still acted as an additional hurdle.

The use of public reinsurance can also limit insurance premiums and, thereby, partly overcome problems with coverage unaffordability. Our evaluation over time shows that this is especially attractive when flood risks increase. Risk-averse insurers increase their premiums when low-probability/high-impact risks increase, especially when these risks are uncertain (Michel-Kerjan and Kunreuther, 2011), as is the case with flood risk in a changing climate (IPCC, 2012). It may be argued that governments can more cheaply reinsure extreme losses (Cardenas et al., 2007) because European governments are, for the most part, risk neutral. Moreover, we find that a public reinsurance facility does not interfere too strongly with the underlying risk signal and incentives for risk reduction. This is the case because primary insurers pay for the government support they receive though risk-based reinsurance premiums, and this reinsurance premium is, in the end, reflected in the premium that households pay. Another advantage of this payment

structure is that the government (and thereby taxpayers overall) receives a fair share of compensation for provided reinsurance. However, risk-based premiums imply that high premiums can occur in areas with a high flood risk when premiums are risk based and people do not mitigate risk, which implies that these premiums could not be affordable or economically viable. This can be overcome in the PPP market structure which places a cap on premiums.

### 3.4. Sensitivity analysis

The results of the sensitivity analysis show that the overall pattern of our main findings is in line with the main assumptions of the model (SI6). The results consistently confirm the desirability of the features common to the semi-voluntary PPP and PPP market structures. The link between premiums and risk reduction in these structures was found to be very important. When this link was removed, the optimal market structure became the solidarity market structure in all cases. This shows that strengthening the link between insurance and risk reduction is important for the continued use of private insurance in the future, when flood risk increases due to climate change. Moreover, the stronger the projected increase in flood risk, the more often the PPP market structure was found to be optimal (SI7.1), indicating the importance of increasing the role of PPPs, both for sharing flood risk and developing institutional frameworks for promoting risk reduction.

The current version of the DIFI model can be updated as more localised or updated information becomes available. Moreover, by comparing the patterns of relative scores rather than specific values, the final recommendations are more robust. One such finding is that strengthening the link between risk-based insurance and risk mitigation is important for keeping premium costs low.

## 4. Discussion

### 4.1. Policy implications

Our findings have relevance to policies in specific countries. For instance, there is some similarity between the PPP market and the United Kingdom's recently introduced Flood Re. Both are based on the mandated purchase of insurance through mortgage conditions with an explicit subsidy for high-risk households. The latter is implemented in Flood Re by charging a supplement on the premiums of low-risk households of approximately £10.50 on average per year, which is close to the estimated cost of €18 (£15) per household per year imposed on low-risk households by the DIFI model. However, we find that the current structure of Flood Re is not optimal for the United Kingdom since incentives for risk reduction are absent. This supports previous research on the matter (Surminski, 2017). The experience with Flood Re also shows that the political motivation to provide public reinsurance coverage can be limited in practise since Flood Re has purchased private-reinsurance-sector coverage.

The solidarity-based market structures of Belgium, France, and Spain are also in need of reform. The reason is that their current market structures may not be suitable for coping with future increases in flood risk due to insufficient incentives for risk reduction. The solidarity principle concerning flood insurance in these countries may be better served by stimulating risk reduction through risk-based premiums whilst addressing equity concerns using additional public policies (e.g., means-tested insurance vouchers or tax credits). The remaining countries with a voluntary purchase requirement (e.g., Germany) should consider promoting or strengthening purchase requirements as, otherwise, the penetration rate remains low, preventing many of the benefits of insurance as a risk-management tool from being realised. For instance, in Hungary, the insurance penetration rate has been increased by making flood insurance coverage a prerequisite to obtain a mortgage (European Commission, 2017a).

Our main policy recommendations may also be applicable outside of



Europe. For instance, the National Flood Insurance Program (NFIP) in the United States has undergone many potential reforms, such as the Biggert-Waters Flood Insurance Reform Act of 2012, the Homeowners Flood Insurance Affordability Act of 2014, and the Flood Insurance Market Parity and Modernization Act of 2016. These acts are aimed at improving the financial sustainability of the NFIP. Moreover, these reforms aim to improve the actuarial soundness of the program by moving towards risk-based premiums whilst strengthening purchase requirements to overcome the observed low penetration rate outside high-risk areas and improving incentives for risk reduction. Michel-Kerjan and Kunreuther (2011) propose a set of reforms for the NFIP similar to those we find favourable for most European countries based on the DIFI model analysis. However, in both cases, these are high-level features of a market structure. Therefore, their implementation will require suitable localisation for them to be politically acceptable and practicable.

Even though we acknowledge that community- and national-level risk-reduction efforts are important for adapting to changing flood risk under climate change, our model mainly focusses on household-level risk reduction and how this can be steered with premium discounts. This is because the incentives provided by premium discounts are commonly discussed advantages of moving towards risk-reflective premiums in the context of flood insurance market reforms around the world, e.g., Flood Re (2018), Lamond et al. (2018), Thieken (2018), European Commission (2017b), and Kunreuther (2017). Moreover, our focus is consistent with a movement towards integrated flood risk management in which residents of flood-prone areas are expected to play a role in limiting flood damage (Bubeck et al., 2016). Our modelling framework shows that human behaviour is an important factor when assessing flood risk, which is in line with recent calls for integrating human behaviour into risk assessments (Aerts et al., 2018). Although we find that exposure growth is a factor that causes flood risk to rise, the floodproofing of properties by households can limit this increase in risk. Efforts to reduce risk are stronger when they are actively incentivised through insurance. For this reason, we study the potential benefits of increasing the connection between risk mitigation and insurance.

However, there is often a concern that, in practise, links between insurance and policyholder-level risk mitigation are insufficient (Surminski et al., 2015). This is commonly argued to be caused by transaction costs involved in insurers monitoring policyholders on a large scale and adjusting premiums accordingly (Hudson et al., 2016). However, this barrier could be overcome if insurers collaborate with other organisations, for example, those that certify the floodproofing of buildings (similar to the home elevation certificates used in the United States), which emphasises the need for closer partnerships (Kunreuther, 2015a). These PPPs are also highly relevant for increasing other aspects of societal resilience. Examples are information sharing about risk and risk-reduction measures, awareness-raising campaigns, offering incentives for risk reduction through terms and policy conditions, setting standards for insurability, and building codes. These are areas in which collaboration between insurance and public-sector stakeholders can not only influence risk reduction behaviour but also risk-generating behaviour, for example, by limiting exposure growth through building codes and zoning policies. Our proposed PPP flood insurance market structures can provide a platform for enabling such integrated flood risk management approaches.

#### 4.2. Model limitations

Although the DIFI model framework enables the evaluation of flood insurance markets across Europe, there are several limitations regarding the interpretation of the results. However, addressing these issues can provide directions for future research.

One limitation is that the modelled insurance market structures are stylised representations of a more complex reality as these do not reflect the individual nuances of the insurance market in each country. The current DIFI model framework limits the complexity of insurance markets by focussing on the market features that have a large influence on the modelled evaluation criteria, such as purchase requirements, the connection of premiums with risk, and the availability of public re-insurance. A challenge is that implementing a higher degree of complexity requires that data on these additional details should be available at the European scale, which is often not the case or is potentially outdated (European Commission, 2013, 2017a, 2017b). For example, insurance coverage levels are difficult to collect and determine due to the unavailability of standardised measures of flood insurance products and their coverage across the European Union (European Commission, 2017b). This can be an important practical limitation because penetration rates in a country could be high, but the total coverage offered by flood insurance can be low, as is the case in Austria (see Insurance Europe (2018b)). However, we attempt to limit the uncertainty from the stylised market structures by mainly looking at the relative benefits of the market structures and the lessons we can learn for 2035–2055 from the overall patterns of desirable reforms we observe. This choice means that the overall implications are less dependent on the original allocation of a country to a stylised market structure.

Similar data limitations apply to individual risk perceptions and adaptation behaviour in household responses to changes in flood risk. For example, to the best of our knowledge, there are no studies linking flood risk perceptions and household-level risk reduction for the Eastern Baltic countries. Therefore, in line with the increasing focus on behaviour in flood risk modelling and management (see, e.g., Aerts et al. (2018)), a wider evidence base on these variables must be developed. The reason is that there is limited knowledge on how subjective perceptions or adaptation behaviours occur across Europe, which must be improved by future research (Aerts et al., 2018). This is especially relevant with respect to the limited temporal dimensions of the available datasets as most studies on risk perception and adaptation behaviour use cross-sectional data collected at one point in time. Nevertheless, even with additional data collection, there will be inherent limitations to validating household-level risk-reduction behaviour and insurance-purchasing patterns at the European scale due to the counterfactual nature of several of the modelled market structures. For example, France has employed a compulsory insurance system since the 1980s (Poussin et al., 2013), which means there is no empirical information about voluntary flood insurance purchases there. The current DIFI framework addresses these uncertainties by using three different risk perception scenarios based on available data. This is done in a similar way to how climate modelling often focusses on the ensemble mean values of a range of models. Moreover, the model focusses mainly on determining and comparing overall patterns in the results between insurance market structures rather than focussing on the absolute value estimates.

Another uncertainty arises from the weights associated with each of the evaluation criteria in our MCA. Currently, we apply general patterns of these weights across the European Union, although they can differ at the country level because of varying local flood risk management objectives. For example, within a specific country, the penetration rate and affordability criteria could be weighted at 0.5 each, whilst the remaining two criteria could be weighted at zero. A weighting scheme like this would find the solidarity market optimal, whilst reversing this particular weighting results in the semi-voluntary (PPP) and PPP markets becoming optimal. Therefore, stakeholder consultation within each country is required to adapt the findings of the DIFI model to their individual context. The current DIFI framework seeks to mitigate this limitation by focussing on overall patterns found across a range of synthetic risk management objectives and how these may be applicable to specific countries.

## 5. Conclusions

The combined effects of socioeconomic development and climate change are expected to increase flood risk in many areas across the world. This growing risk profile has resulted in an increased interest in strategies that can help manage and limit the impacts of flooding. The development of suitable flood insurance mechanisms is one such strategy. Various countries have debated which kind of flood insurance arrangement is best able to cope with future changes in flood risk. To provide insights for this debate, we presented an initial comparative evaluation of stylised flood insurance market structures for Europe through the DIFI model framework, which is a holistic evaluation method of flood insurance arrangements using four important criteria.

The results of the comparative DIFI model suggest a common insurance market reform pathway for insurance as a flood risk management tool with the following features: limited premium cross-subsidisation between high- and low-risk households, involvement of a governmental reinsurer, incentives for policyholders to floodproof homes, and stronger purchase requirements. Even though there is no one-size-fits-all solution, there are common features which can guide local discussions on reforms for flood insurance markets. These common features, such as the movement towards a greater focus on PPPs, involving a range of stakeholders, can lead to the creation of mechanisms that support households to buy insurance and support the insurance industry to provide a wider degree of coverage.

Moreover, due to the focus on stylised market characteristics, our recommendations are applicable outside of Europe. Even though the overall patterns of stylised flood insurance market characteristics appear to be generalisable, their practical implementation will have to be tailor-made according to local risk profiles and public policy preferences (Raadgever et al., 2018).

Several areas of future research were identified based on the development and application of the DIFI model framework. The primary focus of risk reduction has been on the role of premium discounts for households, whilst it is also possible to influence the risk behaviour of governments and businesses through insurance. There are initial steps in this direction (see, e.g., Unterberger et al. (2019)), and future research in this area should be further developed. Additionally, residential flood insurance only protects against certain elements of overall flood impacts, although there are also large potential impacts through the disruption of infrastructure, governmental services, and so forth which can be addressed in future studies.

Furthermore, future research can examine the most cost-effective ways of reducing the transaction costs involved in stimulating policyholder risk-reduction behaviour through risk-based premiums, e.g., using certification of floodproof building practises. Moreover, mechanisms other than premium discounts may be effective in promoting risk reduction, which can be evaluated in future studies. An example is that insurers may raise policyholders' risk awareness by better informing them about the flood risk they face. In relation to this point, improving knowledge about individual flood risk perceptions across Europe and how these may be influenced by risk communication campaigns could strengthen the empirical basis of this component in the DIFI model.

A common finding of the DIFI model is that PPPs stand to play a large role in future flood insurance reforms. The above research suggestions can build upon this finding by extending the range of partners involved to create a suitable enabling environment to strengthen the link between insurance and risk reduction (see, for example, discussions presented in Flood Re (2018), Surminski and Thieken (2017), or The Geneva Association (2018)).

Finally, the focus of this paper was on fluvial flooding, but in the light of climate change and increasing urbanisation, coastal and pluvial flood risks stand to grow in importance. Thus, future research can focus on understanding how these particular flood risks can be integrated into a modelling framework like DIFI. This distinction is important because

coastal flooding and adaptation follow a different process to fluvial flooding, whilst pluvial flooding processes follow localised phenomena. In general, we believe that future research on multi-hazard risk assessments can offer a useful basis for insurance modelling and adaptation studies.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.gloenvcha.2019.101966>.

## References

- Aerts, J.C.J.H., Botzen, W., Clarke, K.C., Cutter, S.L., Hall, J.W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., Kunreuther, H., 2018. Integrating human behaviour dynamics into flood disaster risk assessment. *Nat. Clim. Change* 8, 193–199.
- Alfieri, L., Dottori, F., Betts, R., Salamon, P., Feyen, L., 2018. Multi-model projections of River Flood Risk in Europe under global warming. *Climate* 6, 6.
- Baur, E., 2016. The Role of Insurance in Disaster Risk Financing. IDRC, Davos, CH.
- Botzen, W.J.W., 2013. Managing Extreme Climate Change Risks Through Insurance. Cambridge University Press, New York.
- Botzen, W.J.W., Aerts, J.C.J.H., van den Bergh, J.C.J.M., 2009. Dependence of flood risk perceptions on socioeconomic and objective risk factors. *Water Resour. Res.* 45.
- Botzen, W.J.W., Kunreuther, H., Michel-Kerjan, E., 2015. Divergence between individual perceptions and objective indicators of tail risks: evidence from floodplain residents in New York City. *Judgm. Decis. Mak.* 10, 365–385.
- Bubeck, P., Aerts, J.C.J.H., de Moel, H., Kreibich, H., 2016. Preface: flood-risk analysis and integrated management. *Nat. Hazards Earth Syst. Sci.* 16, 1005–1010.
- Bubeck, P., Botzen, W.J.W., Kreibich, H., Aerts, J.C.J.H., 2012. Long-term development and effectiveness of private flood-risk reductions: an analysis for the German part of the river Rhine. *Nat. Hazards Earth Syst. Sci.* 12, 3507–3518.
- Cardenas, V., Hochrainer, S., Mechler, R., Pflug, G., Linnerooth-Bayer, J., 2007. Sovereign financial disaster risk management: the case of Mexico. *Environ. Hazards* 7, 40–53.
- CRED-UNISDR, 2015. The Human Cost of Weather Related Disasters, 1995–2015. Centre for Research on the Epidemiology of Disasters and United Nations Office for Disaster Risk Reduction.
- Cremades, R., Surminski, S., Mániz Costa, M., Hudson, P., Shrivastava, P., Gascoigne, J., 2018. Using the adaptive cycle in climate-risk insurance to design resilient futures. *Nat. Clim. Change* 8, 4–7.
- DEFRA, 2011. Flood Risk and Insurance: a Roadmap to 2013 and Beyond Final Report of the Flood Insurance Working Groups PB 13684. Department for Environment, Food and Rural Affairs, London.
- European Commission, 2013. Green Paper on the Insurance of Natural and Man-made Disasters (Communication No. COM(2013) 213 Final). European Commission, Strasbourg.
- European Commission, 2017a. In: Le Den, X., Persson, M., Benoist, A., Hudson, P., de Ruiter, M., de Ruig, L., Kuik, O., Botzen, W. (Eds.), Insurance of Weather and Climate-Related Disaster Risk: Inventory and Analysis of Mechanisms to Support Damage Prevention in the EU. Publications Office of the European Union, Luxembourg.
- European Commission, 2017b. Study to Support the Evaluation of the EU Adaptation Strategy, Summary. European Commission.
- European Commission, 2015. In: Cardoso, R., Ren, Y. (Eds.), State Aid: Commission Approves UK Flood Reinsurance Scheme. IP-15-3884.EN. European Commission, Brussels.
- FEMA, 2016. Special Flood Hazard Area. <http://www.fema.gov/special-flood-hazard-area>.
- FEMA, 2018. An Affordability Framework for the National Flood Insurance Program. Department of Homeland Security, Washington, DC.
- Feyen, L., Dankers, R., Bódis, K., Salamon, P., Barredo, J.I., 2012. Fluvial flood risk in Europe in present and future climates. *Clim. Change* 112, 47–62.
- Flood Re, 2018. Incentivising Household Action on Flooding and Options for Using Incentives to Increase the Take up of Flood Resilience and Resistance Measures. Flood Re.
- GDV, 2013. Naturgefahrenreport 2013 — Die Schaden-Chronik der deutschen Versicherer mit Zahlen, Stimmen und Ereignissen. available at: German Insurance Association (GDV). <http://bit.ly/1i7lch2>.
- Golnaraghi, M., Surminski, S., Schanz, K., 2017. An Intergrated Approach to Managing Extreme Events and Climate Risks. The Geneva Association, Zurich.
- Hochrainer-Stigler, S., Lorient, A., 2018. Evaluating partnerships to enhance disaster risk



- management using multi-criteria analysis: an application at the Pan-European level. *Environ. Manage.* 61, 24–33.
- Hochrainer, S., Linnerooth-Bayer, J., Mechler, R., 2010. The European union solidarity fund. *Mitig. Adapt. Strat. Glob. Change* 15 979–810.
- Hudson, P., 2018. A comparison of definitions of affordability for flood risk adaption measures: a case study of current and future risk-based flood insurance premiums in Europe. *Mitig. Adapt. Strateg. Glob. Change* 23, 1019–1038.
- Hudson, P., Botzen, W.J.W., Feyen, L., Aerts, J.C.J.H., 2016. Incentivising flood risk adaptation through risk based insurance premiums: trade-offs between affordability and risk reduction. *Ecol. Econ.* 125, 1–13.
- Insurance Europe, 2018a. Insurance and Natural Catastrophes Insurance Europe, Brussels.
- Insurance Europe, 2018b. NatCat Chart — Property Insurance, Private Lines. Insurance Europe, Brussels.
- Insurance Europe, 2018c. Response to the European Commission's Consultation on the Evaluation of the EU's Strategy on Adaptation to Climate Change. Insurance Europe.
- IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.
- IPCC, 2018. Global Warming of 1.5C. IPCC, Switzerland.
- Johnson, C., Penning-Rowell, E., Parker, D., 2007. Natural and imposed injustices: the challenges in implementing 'fair' flood risk management policy in England. *Geogr. J.* 173, 374–390.
- Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W., Bouwer, L., Pflug, G., Rojas, R., Ward, P.J., 2014. Increasing stress on disaster-risk finance due to large floods. *Nat. Clim. Change* 4, 264–268.
- Kousky, C., Kunreuther, H., 2014. Addressing affordability in the national flood insurance program. *J. Extreme Events* 1, 1450001.
- Kousky, C., Kunreuther, H., Lingle, B., Shabman, L., 2018. The Emerging Private Residential Flood Insurance Market in the United States, Wharton Risk Management and Decision Processes Center Wharton, Risk Management and Decision Processes Center. University of Pennsylvania, Philadelphia, US.
- Kreibich, H., Thieken, A.H., Petrow, T., Müller, M., Merz, B., 2005. Flood loss reduction of private households due to building precautionary measures—lessons learned from the Elbe flood in August 2002. *Nat. Hazards Earth Syst. Sci.* 5, 117–126.
- Kron, W., 2005. Flood risk = hazard • values • vulnerability. *Water Int.* 30, 58–68.
- Kunreuther, H., 2008. Reducing losses from catastrophic risks through long-term insurance and mitigation. *Soc. Res.* 75, 905–930.
- Kunreuther, H., 2015a. The role of insurance in reducing losses from extreme events: the need for public-private partnerships. *Geneva Pap. Risk Insur. Issues Pract.* 40, 741–762.
- Kunreuther, H., 2015b. The role of insurance in reducing losses from extreme events: the need for public-private partnerships. *Geneva Pap. Risk Insur. Issues Pract.* 40, 471.
- Kunreuther, H., 2017. Encouraging Adaptation to Flood Risk: The Role of the National Flood Insurance Program, Wharton Working Papers. Wharton, University of Pennsylvania, Philadelphia, USA.
- Lamond, J., Rose, C., Bhattacharya-Mis, N., Joseph, R., 2018. Evidence Review for Property Flood Resilience Phase 2 report. Flood Re and UWE Bristol.
- Lamond, J.E., Penning-Rowell, E.C., 2014. The robustness of flood insurance regimes given changing risk resulting from climate change. *Clim. Risk Manag.* 2, 1–10.
- Mechler, R., Bouwer, L.M., Linnerooth-Bayer, J., Hochrainer-Stigler, S., Aerts, J.C.J.H., Surminski, S., Williges, K., 2014. Managing unnatural disaster risk from climate extremes. *Nat. Clim. Change* 4, 235–237.
- Michel-Kerjan, E., Czajkowski, J., Kunreuther, H., 2015. Could flood insurance be privatised in the United States? A primer. *Geneva Pap. Risk Insur. Issues Pract.* 40, 179–208.
- Michel-Kerjan, E., Kunreuther, H., 2011. Redesigning flood insurance. *Science* 333, 408–409.
- O'Neill, J., O'Neill, M., 2012. In: Foundation, J.R. (Ed.), *Social Justice and the Future of Flood Insurance*, York, UK.
- Osberghaus, D., 2015. The determinants of private flood mitigation measures in Germany — evidence from a nationwide survey. *Ecol. Econ.* 110, 36–50.
- Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H., 2013. Estimation of insurance premiums for coverage against natural disaster risk: an application of Bayesian Inference. *Nat. Hazards Earth Syst. Sci.* 13, 737–754.
- Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H., Dijkstra, T., 2015. Risk allocation in a public-private catastrophe insurance system: an actuarial analysis of deductibles; stop-loss; and premium. *J. Flood Risk Manag.* 8, 116–134.
- Porrini, D., Schwarze, R., 2014. Insurance models and European climate change policies: an assessment. *Eur. J. Law Econ.* 38, 7–28.
- Poussin, J.K., Botzen, W.J.W., Aerts, J.C.J.H., 2013. Stimulating flood damage mitigation through insurance: an assessment of the French CatNat system. *Environ. Hazards* 12, 258–277.
- Raadgever, G.T., Booister, N., Steenstra, M.K., 2018. Flood risk management strategies. In: Raadgever, T., Hegger, D. (Eds.), *Flood Risk Management Strategies and Governance*. Springer International Publishing, Cham, pp. 93–100.
- Raschky, P.A., Schwarze, R., Schwindt, M., Zahn, F., 2013. Uncertainty of governmental relief and the crowding out of flood insurance. *Environ. Resour. Econ.* 54, 179–200.
- Raschky, P.A., Weck-Hannemann, H., 2007. Charity hazard—a real hazard to natural disaster insurance? *Environ. Hazards* 7, 321–329.
- Rojas, R., Feyen, L., Watkiss, P., 2013. Climate change and river floods in the European Union: socio-economic consequences and the costs and benefits of adaptation. *Glob. Environ. Change* A 23, 1737–1751.
- Savage, L.J., 1954. *The Foundation of Statistics*. John Wiley, New York.
- Sayers, P., Penning-Rowell, E.C., Horritt, M., 2018. Flood vulnerability, risk, and social disadvantage: current and future patterns in the UK. *Reg. Environ. Change* 18, 339–352.
- Schanz, K., 2018. Understanding and Addressing Global Insurance Protection Gaps. Research in Brief The Geneva Association Zurich, CH.
- Schwarze, R., Wagner, G.G., 2007. The political economy of natural disaster insurance: lessons from the failure of a proposed insurance scheme in Germany. *Environ. Policy Gov.* 17, 403–415.
- Surminski, S., 2017. Fit for Purpose and Fit for the Future? An Evaluation of the UK's New Flood Reinsurance Pool. Resources for the Future.
- Surminski, S., Aerts, J.C.J.H., Botzen, W.J.W., Hudson, P., Mysiak, J., Pérez-Blanco, C.D., 2015. Reflection on the Current Debate on How to Link Flood Insurance and Disaster Risk Reduction in the European Union. *Natural Hazards* 79, pp. 1451–1479.
- Surminski, S., Bouwer, L., Linnerooth-Bayer, J., 2016. How insurance can support climate resilience. *Nat. Clim. Change* 6, 333–334.
- Surminski, S., Eldridge, J., 2015. Flood insurance in England: an assessment of the current and newly proposed insurance scheme in the context of rising flood risk. *J. Flood Risk Manag.*
- Surminski, S., Thieken, A., 2017. Promoting flood risk reduction: the role of insurance in Germany and England. *Earth's Future* 5, 979–1001.
- Thaler, T., Fuchs, S., Priest, S., Doorn, N., 2018. Social justice in the context of adaptation to climate change—reflecting on different policy approaches to distribute and allocate flood risk management. *Reg. Environ. Change* 18.
- Thaler, T., Hartmann, T., 2016. Justice and flood risk management: reflecting on different approaches to distribute and allocate flood risk management in Europe. *Nat. Hazards* 83, 129–147.
- The Geneva Association, 2018. Climate Change and the Insurance Industry: Taking Action as Risk Managers and Investors Perspectives from C-level Executives in the Insurance Industry. The Geneva Association.
- Thieken, A., 2018. Contributions of flood insurance to enhance resilience—findings from Germany. In: Fekete, A., Fiedrich, F. (Eds.), *Urban Disaster Resilience and Security*. Springer, pp. 129–143.
- UNFCCC, 2018. Paris Agreement. UNFCCC.
- UNISDR, 2015. Sendai Framework for Disaster Risk Reduction 2015–2030. United Nations, United Nations — Headquarters (UN).
- Unterberger, C., Hudson, P., Botzen, W.J.W., Schroeer, K., Steininger, K.W., 2019. Future public sector flood risk and risk sharing arrangements: an assessment for Austria. *Ecol. Econ.* 156, 153–163.
- Von Peter, G., von Dahlen, S., Saxena, S., 2012. Unmitigated Disasters? New Evidence on the Macroeconomic Cost of Natural Catastrophes, BIS Working Papers No. 394. Bank for International Settlements (BIS), Basel.
- Vousdoukas, M.I., Mentaschi, L., Voukouvelas, E., Bianchi, A., Dottori, F., Feyen, L., 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nat. Clim. Change* 8, 776–780.
- Wilby, R.L., Keenan, R., 2012. Adapting to flood risk under climate change. *Prog. Phys. Geogr.* 36, 348–378.
- Winsemius, H.C., Aerts, J.C.J.H., van Beek, L.P.H., Bierkens, M.F.P., Bouwman, A., Jongman, B., Kwadijk, J.C.J.K., 2016. Global drivers of future river flood risk. *Nat. Clim. Change* 6, 381–385.
- Zhao, W., Kunreuther, H., Czajkowski, J., 2016. Affordability of the national flood insurance program: application to Charleston County, South Carolina. *Nat. Hazards Rev.* 17, 1–14.